The Enhancement of High Energy Electron Fluxes and the Variation of the Atmospheric Electric Field in the Antarctic Region

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Abstract: High-energy electron precipitation in the high latitude regions enhances the ionization of the atmosphere, and subsequently increases the atmospheric conductivities and the vertical electric field of the atmosphere near the ground as well. The high-energy electron flux (HEEF) data measured by the Feng-Yun III meteorological satellite are analyzed together with the data of near-surface atmospheric vertical electric field measured at the Russian Vostok Station. Three HEEF enhancements are identified and show that when the HEEF increases to a certain level, the local atmospheric vertical electric field near the ground can increase substantially than usual. The time of the response of the electric field to the HEEF enhancement is about 3.7 to 4 days (delay time).

Keywords: high-energy electron flux (HEEF), polar precipitation, atmospheric electric field

Classified index:

0. Introduction

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It has been demonstrated that the solar energy particles are able to affect the mesospheric electric field, and also affect the atmospheric vertical electric field near the ground. The solar proton events (SPE) are capable of creating a measurable change to the electric field at ground level (~5% change)[1]. One result of SPE incident in the middle atmosphere is the generation of enhanced charged particle densities, and a substantial increase in the middle and upper atmospheric conductivities [2]. *Holzworth* and *Reagan* expressed that the atmospheric electric field changes because the atmospheric conductivities have changed [2, 3]. *Frank* regarded that the interplanetary magnetic field could also change the vertical atmospheric electric field [4].

A working model linking the ground to the atmosphere is the global electric circuit (GEC), which is one result of the thunderstorm activities [4]. This model is illustrated in Fig. 1.[5-7]. The thunderstorms act as a voltage source, V, driving current upward from the ground through the upper atmosphere (R_h). The current path extends through the stratosphere and is completed via downward currents in the fair-weather atmosphere ($R_s^{loc} + R_t$) in regions well away from the storm[4].

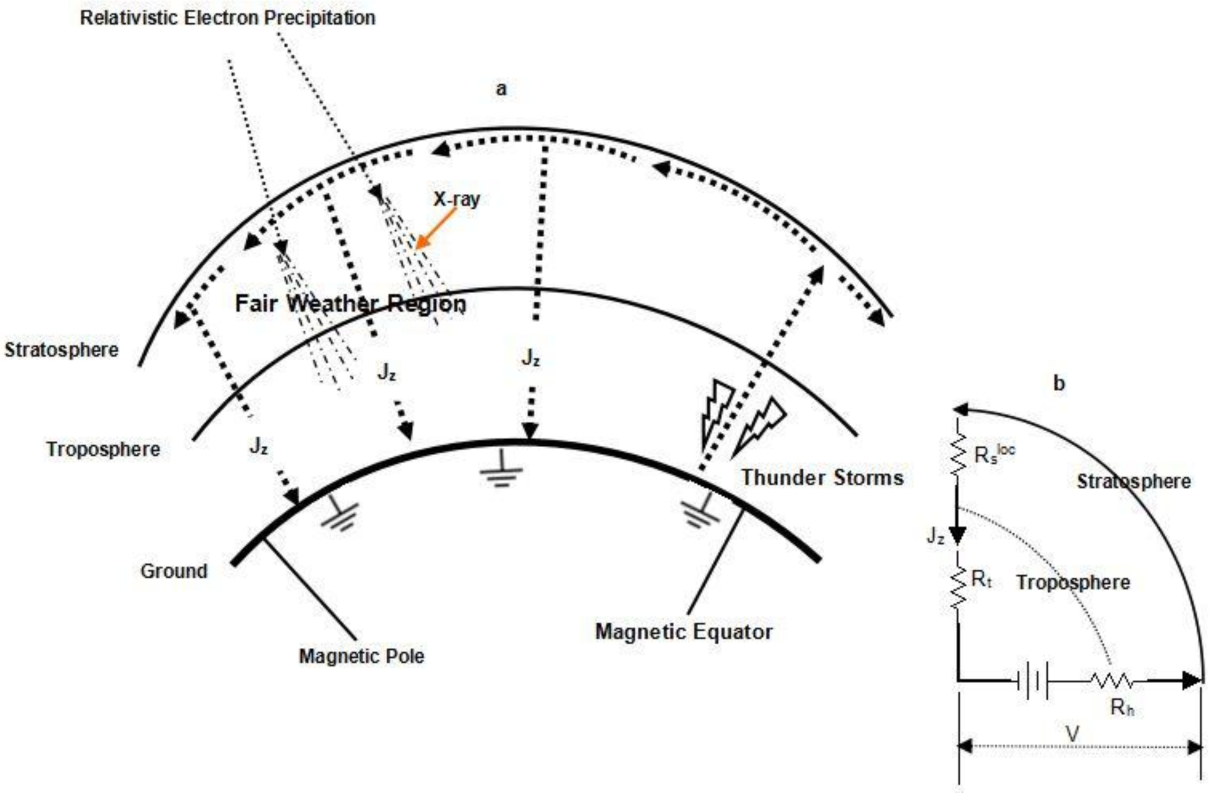

Fig. 1. (a) Diagram illustrating the global electric circuit. (b) The simplified equivalent circuit for Fig1.a.

The vertical electric field of the atmosphere near the ground is mainly decided by the current density J_z. There are many independent ways in which the solar wind modulates the flow of current density J_z in the GEC[5, 6, 8], such as (a) the galactic cosmic ray[9, 10], from which many complex numerical simulations have been done[11, 12], (b) the relativistic electron precipitation[8, 13-15], and (c) changes in the ionospheric potential distribution due to the magnetosphere-ionosphere coupling[5, 16, 17]. *Farrell* and *Desch* has found that the SPE can decrease the R_h in the thunderstorm region, and then J_z will increase [1]. The equation of the conductivity is:

$$\sigma = \sigma_0 \exp(z / z_0) \qquad (1)$$

The conductivity near the ground keeps as a constant, according to the Ohm law:

$$\mathrm{J}_z = \sigma E_z \qquad (2)$$

If the J_z increases, the vertical electric field of the atmosphere near the ground (E_z) increases absolutely.

The relativistic electron precipitation can effectively enhance the ionization of the stratosphere by generating X-ray. With an increase of the ionization in the stratosphere, the local resistance between the stratosphere and the troposphere (R_s^{1oc}) decreases, and thereby increase J_z. According to the equation (2), the vertical electric field of the atmosphere near the ground can be affected--it will increase. The weather in the storm regions could also be affected. The precipitation of relativistic electrons can excite X-rays in the atmosphere, which will then increase the ionization in the lower atmosphere [6, 18-21], as shown in Fig. 2.

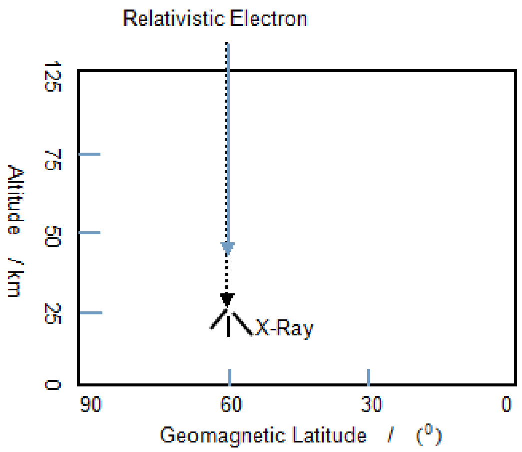

Fig. 2. The vertical height range of the relativistic electron precipitation effect.

In Fig. 1, the relativistic electron enhances the ionization of the stratosphere by generating X-rays. With the enhancement of the ionization in the stratosphere, the local resistance between stratosphere and troposphere (R_s^{loc}) decreased, and then J_z increased. After that, the vertical electric field of the atmosphere near the ground would be affected, the electric field would increase, and the weather in the storm regions will be affected. According to the Gauss equation,

$$\rho(z)\ /\ \varepsilon_0 = \nabla \bullet \vec{E} \quad (3)$$

where $\rho(z)$ represents the space charge generated by the electric field gradient. The electric field gradient changes the distribution of the charge in the clouds, affects the microphysics of the clouds, and then changes the parameter of the weather and the climate[5, 8, 21], such as the atmospheric vortices[6, 13, 15, 22], the cloud cover[6, 23], and the atmospheric transparency[6, 24].

1. Data Presentation

The HEEF data measured by the Feng-Yun Ⅲ satellite in 2012, and the vertical electric field of the atmosphere near the ground measured at the Russian Vostok Station ($78^0 S, 106^0 E$) in 2012 have been used and well analyzed. The HEEF data during the period of satellite flying over the Russian Vostok Station (the satellite passed the longitude between $100^{\circ} E$ and $115^{\circ} E$, latitude between $70^{\circ} S$ and $90^{\circ} S$, seen in Fig. 3) has been selected, the satellite passed through this region nearly 2190 times in the year 2012, and the data-fitting method has been used to study the tendency of these HEEF data. Three HEEF enhancement events have been found and only one event has strong enhancement (the event 1 of HEEF enhancement had been illustrated in Fig. 4,

the event 2 of HEEF enhancement had been illustrated in Fig. 5, and the Fig. 6 illustrated the event 3 of HEEF enhancement).

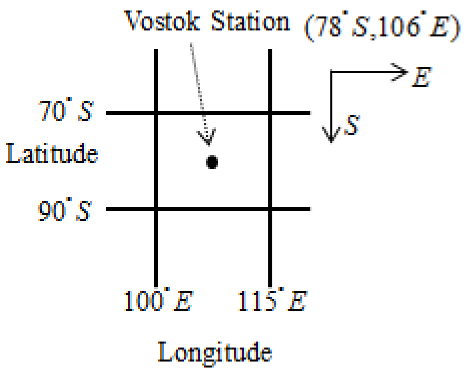

Fig. 3. The position of the Russian Vostok Station, and the HEEF data has been selected during the period of the satellite flying over the Russian Vostok Station (the satellite passed the longitude between $100^{\circ}E$ and $115^{\circ}E$, latitude between $70^{\circ}S$ and $90^{\circ}S$).

In the Fig. 4 to 6, The top four panels show the HEEF at different energy channels, (a) 0.15 - 0.35 MeV, (b) 0.35 - 0.65 MeV, (c) 0.65 - 1.2 MeV, (d) 1.2 - 2.0 MeV, the black dashed lines represent the tendency of the HEEF by using the data fitting method, and the red vertical lines on the left and right sides stand for the approximate time when the HEEF begins to increase, and the time when the electric field begins to enhance, respectively. Plot 'e' shows the vertical electric field of the atmosphere near the ground. Plots 'f' to 'h' represent the parameters of solar wind, (f) interplanetary magnetic field component, (g) the solar wind velocity, (h) the kinetic pressure of solar wind, these solar wind parameters come from ACE(Advanced Composition Explorer, USA); Plots 'i' to 'j' represent the parameters of geomagnetic activity, (i) Dst index and (j) the AE index from WDC Kyoto (these data were all download from: http://omniweb.gsfc.nasa.gov/form/omni_min.html). Fig. 4 and Fig. 5 have shown that when the HEEF increases to a certain level, the vertical electric field of the atmosphere near the ground will increase substantially. The delay time that the electric field begins to increase after HEEF enhancement is about 3.7 to 4 days.

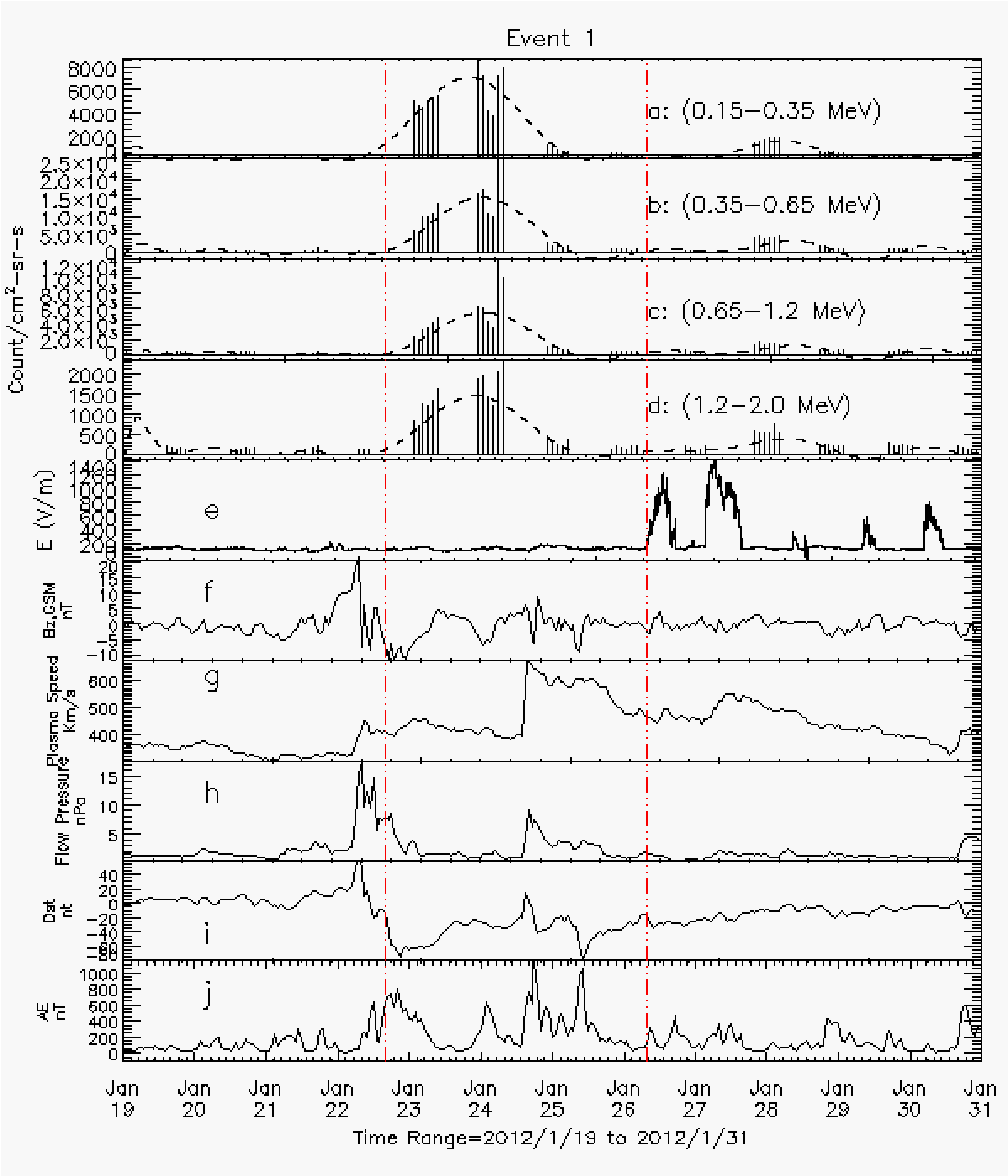

Fig. 4. The top four panels show the HEEF variation of different energy, (a) 0.15-0.35 MeV, (b) 0.35-0.65 MeV, (c) 0.65-1.2 MeV, (d) 1.2-2.0 MeV. Plot 'e' is the ground electric field. Plots 'f' to 'h' represent the parameters of solar wind, (f) interplanetary magnetic field component, (g) the solar wind velocity, (h) the kinetic pressure of solar wind. Plots 'i' to 'j' represent the parameters of geomagnetic activities, (i) Dst index and (j) the AE index. During the period from Jan 19 to Jan 31, there was an interplanetary disturbance from the sun on Jan 22, the Bz varied from +20 nT to -10 nT, the solar wind speed varied from 300 km/h to 450 km/h, the pressure of the plasma

enhanced from 2 nPa to 17 nPa, afterwards, there was a geomagnetic storm generated near the time that the left red dashed line indicated, the Dst was about -40 nT, and the AE index was about 500 nT, the geomagnetic storms led to the HEEF enhance. The event 1 occurred in the interval between the two red dashed lines, the HEEF began to increase at the time that the left red dashed line indicated, after the HEEF declined to the level before enhancement, the electric field began to increase substantially at the time that the right dashed line indicated. There were two electric field enhancements in this event, the first one lasted about 12.5 hours, and the second one lasted about 15.3 hours. The time between the two red dashed lines was about 3.7 days.

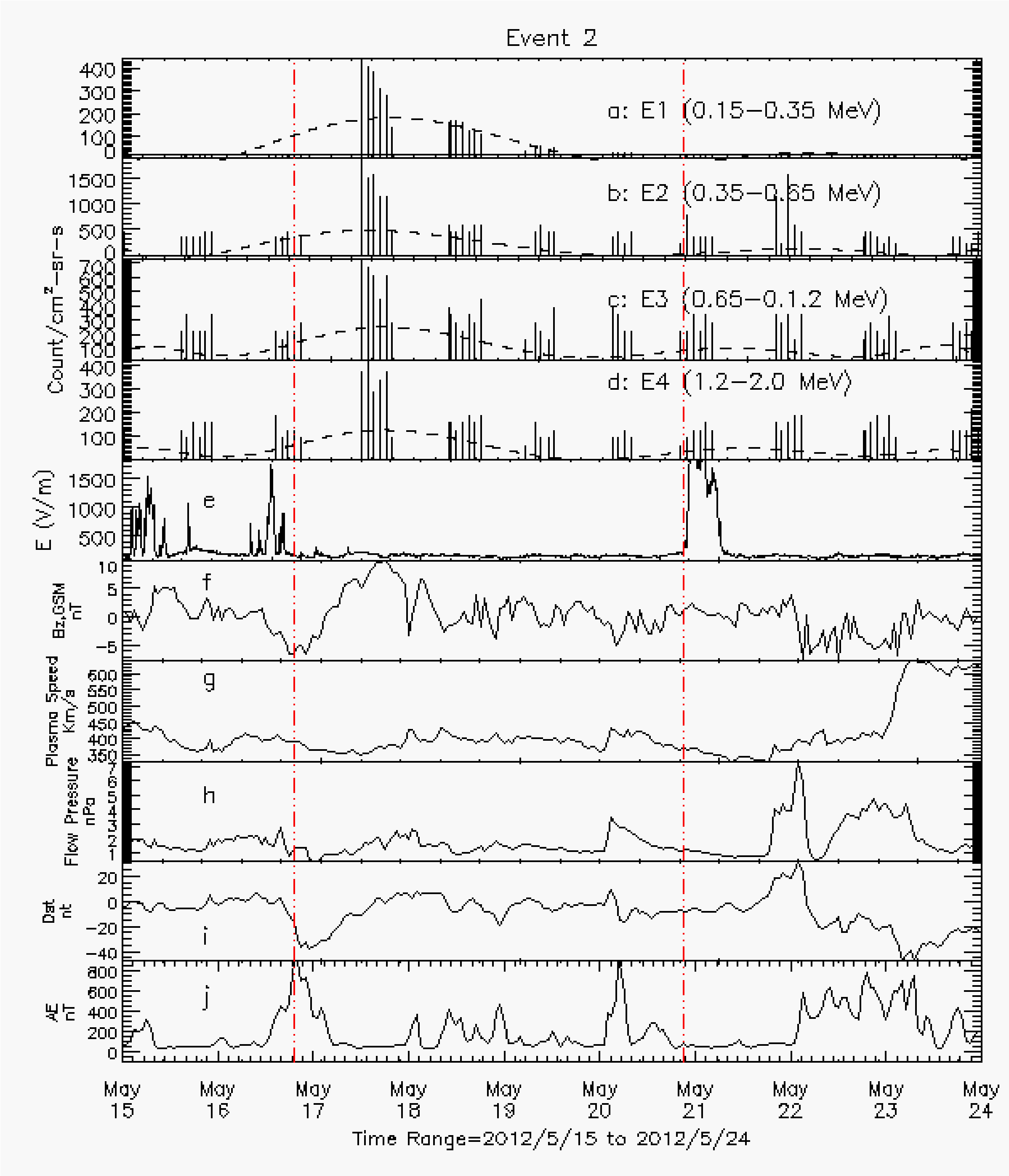

Fig. 5. Same as Fig. 4, during the period from May 15 to May 24. There was a geomagnetic storm generated near the time that the left red dashed line indicated, the Bz was about -5 nT, the solar wind speed was about 380 km/h, the pressure of the plasma was about 1 nPa, the Dst was about -20 nT, and the AE index was about 1000 nT, these geomagnetic activities led to the following enhancement of the HEEF. The ground electric field had some fluctuations between May 15 and May 17, it might be caused by other factors (for example, the winds). The event 2 occurred in the interval between the two red dashed lines, the Electric field hardly changed during

the time that the HEEF enhancement and decline, but began to increase after the time that the right red dashed line indicated. The enhancement lasted about 10.7 hours. The time between the two red dashed lines was about 4 days.

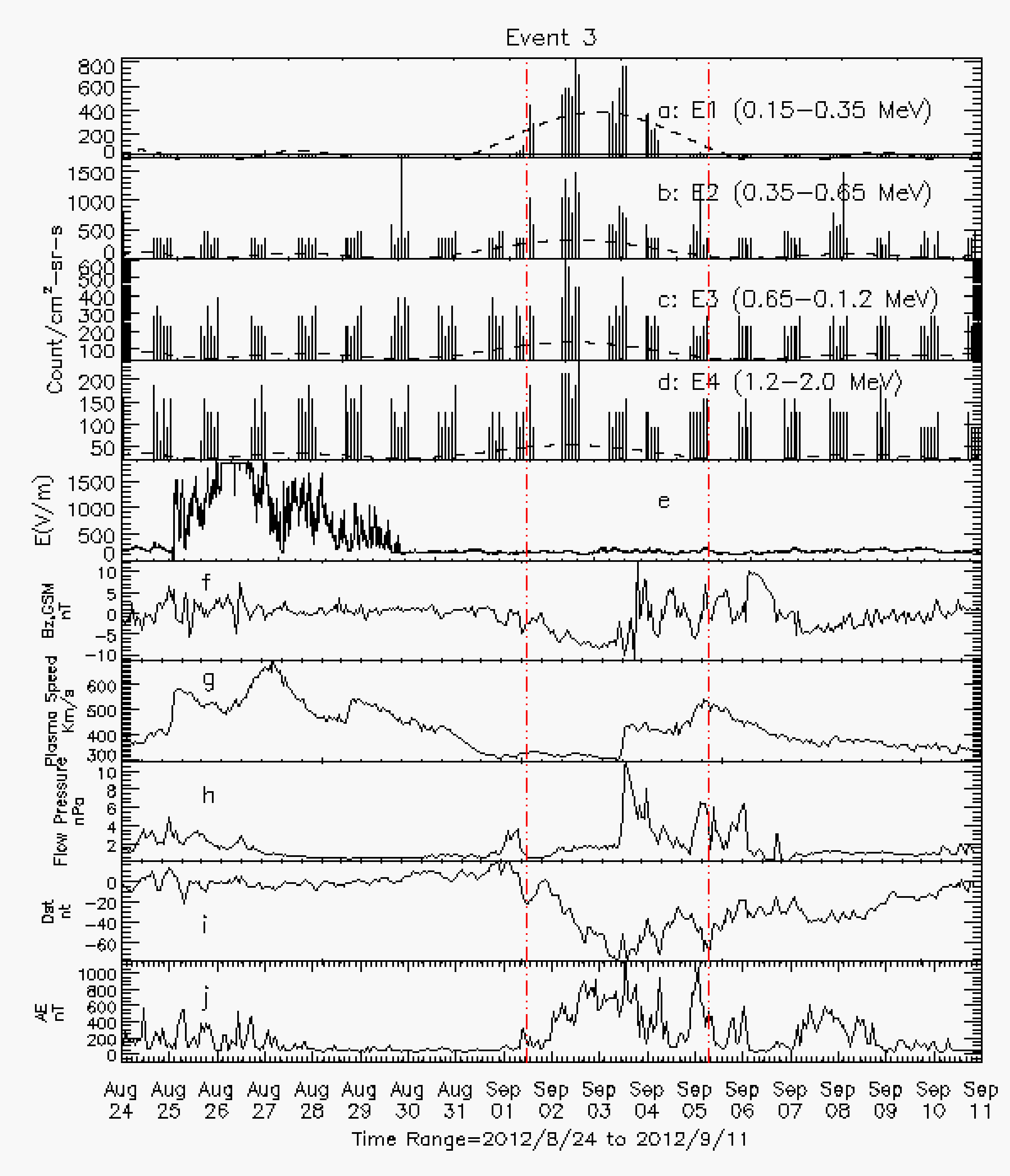

Fig. 6. Same as Fig. 4, during the period from Aug 24 to Sep 11. The electric field of the ground fluctuated before the HEEF began to increase between Aug 25 and Aug 30, it may be caused by other factors. Near the time that the left red dashed line indicated, the Bz was about -4

nT, the solar wind velocity was about 340 km/h, the pressure of the plasma was about 1 nPa, the Dst was about -20 nT, and the AE index was about 400 nT. The geomagnetic activities generated near the time that the left red dashed line indicated, which led to the HEEF enhancement, but didn't enhance obviously, afterwards, the HEEF declined to the level before enhancement, and the ground electric field didn't have changed.

As shown in Fig. 4, the event 1 is more representative and more obvious. Before the right red dashed line, the electric field almost changeless and the magnitude was about 120 V/m. There were no other factors that affected it. After about 3.7 days where the HEEF began to enhance, the electric field began to increase substantially. The peak value of the first enhancement was about 1200 V/m, and lasted about 12.3 hours; the peak value of the second enhancement was about 1400 V/m, and lasted about 15.3 hours. Afterwards, the electric field declined to the level before enhancement. Shown in Fig. 5, that detailed there were some enhancements before the HEEF began to increase, it might be caused by other factors, which was probably the wind (the wind data has been checked from:http://www.wunderground.com/history/station/89606/2012/4/26/MonthlyHistory.html). But the electric field almost changeless during the HEEF change and started to increase at the time that the left red dashed line indicated. The enhancement lasted about 10.7 hours, and then the electric field declined to the level before enhancement.

While there were some enhancements of the HEEF in the event 3 (seen in Fig. 6), the electric field had no fluctuations. It may be because that the HEEF did not increase to a certain level that can cause the electric field to enhance. We also consider that the HEEF may be not the only factor that caused the electric field to enhance. Nevertheless, if the HEEF increases to a certain level (flux is high nearly 10^4 $counts/cm^2 \bullet sr \bullet s$ in the data analysis), the electric field can enhance substantially. It generally takes about 3.7 to 4 days for the electric field to enhance following the HEEF enhancement.

Based on the transport path of the high-energy electron shown in Fig. 1, the following physical processes can be understood: The high-energy electron fluxes firstly enhance in the Earth's radiation belts during magnetic storms. After some plasma waves in space diffuse these

high energy electrons into the loss cone for atmospheric loss, the precipitation produces X-rays. Furthermore, the X-ray emissions increase the ionization of the middle-upper atmosphere at high latitude regions, decrease the local resistance R_z^{loc}, increase the current density J_z, and then result in the substantial increase of the vertical electric field of the atmosphere near the ground.

2. Discussion and Conclusion

The HEEF data measured by Feng-Yun III satellite and the vertical electric field of the atmosphere near the ground measured at the Russian Vostok station ($78^0 S, 106^0 E$) have been adopted for analyses. The potential influence of the HEEF enhancement on the vertical atmospheric electric field near the ground has been investigated for three identified HEEF enhancements. By comparing them with the vertical electric field of the atmosphere near the ground, it has been found that while the HEEF enhancement may be not the only factor that causes the electric field increase, if the HEEF increases to a certain level, the electric field can enhance substantially. The delay time that the electric field begins to increase after the HEEF enhancement is about 3.7 to 4 days.

It will take some time for the electrons to diffuse and decay. The Feng-Yun III satellite is a low altitude satellite, the life time of the high energy electrons at low altitude has been modeled by Tu et al.[2010], and their case study showed that the lifetime of the electron was less than 10 days but longer than 1 day for almost all energy electrons[25]. In another paper, Li et al.[2001] found that the average electron life time is approximately 2.67 days at geostationary orbit[20]. The high energy electrons in event 1 enhanced around Jan 23, after about 2 days, the electrons began to precipitation, it might take about 1 or 2 days for the precipitated electrons to arrive in atmosphere, then affect the local conductivity. Therefore, according to the data analyze, the time from the HEEF enhancement to the ground electric field fluctuations is about 3.7 to 4 days (delay time).

Based on the physical model, our data presentation can be used to explain how the HEEF affects the vertical electric field of the atmosphere near the ground. The event 1 (seen in Fig. 4) shows that the HEEF is a major factor that can affect the electric field of the atmosphere (that has excluded the possibility of wind induction).

The region that high energy electron collide with the atmosphere and lead direct ionization is above 50 km, however, the X-ray produces ionization down to 20 km (seen in Fig. 2). The high

energy electrons can affect J_z by modulating the conductivity between about 20 km and 60 km[5]. The low energy electrons between 1 keV and 10 keV cannot excite X-ray, it makes less contribution to modulate the conductivity compared to high energy electrons.

During the storm time, the high energetic electrons precipitating from the inner and outer radiation belts interact with the middle and lower atmosphere. On one hand, the precipitated electrons affect the ionization by produce direct ionization, and on the other hand, the precipitated electrons affect the ionization indirectly by bremsstrahlung radiation [26]. The high energy electrons whose initial energy was E_{k1} collided with the atomic nucleus, afterwards, the electrons lost their energy, their energy became E_{k2} and excited X-ray ($E_{k1} - E_{k2} = h\upsilon$ seen in Fig. 7), the X-ray reacted with molecules in the atmosphere as follow：

$$h\upsilon + O_2 \rightarrow O + O \tag{4.1}$$

$$h\upsilon + O \rightarrow O^+ + e \tag{4.2}$$

$$h\upsilon + N_2 \rightarrow N + N \tag{4.3}$$

$$h\upsilon + N \rightarrow N^+ + e \tag{4.4}$$

The processes of equation 4.2 and 4.4 lead to ionization enhancement. The conductivity is strongly modulated by the high energy electron precipitation which accompanies high energy electron density enhancements. The high energy electrons precipitating from the radiation belt with associated X-ray bremsstrahlung, they lead to enhanced ionization in the middle and upper atmosphere and consequently to chemical changes [27-29], and affect the local conductivity in stratosphere. Therefore, the increases of the electron and ion density caused by the high energy particle precipitation increases the local upper layer atmosphere electrical conductivity[30].

The HEEF and the X-ray enhance the ionization of the stratosphere, increase the conductivity, decrease the resistance (R_s^{loc}), then the ionosphere-earth current density J_z increased, afterwards, led to the ground electric field enhancement, the schematic of which is shown in Fig. 7.

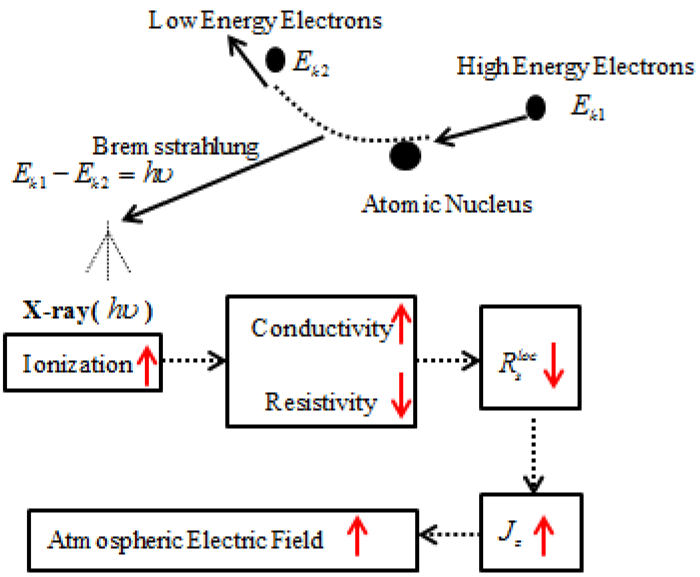

Fig. 7. Schematic showing the mechanism of how the high-energy electron precipitation affects the vertical electric field of the atmosphere. The upward arrow represents an increase; the downward arrow represents a decrease.

Meteorological effects show correlations between changes in the vertical electric field of the atmosphere and the cloud micro-structure. The varied static electric field can affect the electro-scavenging process near droplets, air ions, and aerosol particles. The reconstruction of space charge of clouds due to the precipitation-associated change of the vertical electric filed can lead to potential variations of cloud micro-structure. And it may subsequently affect the ambient temperature evolution which has consequences for weather and climate in different scales. The electric field variations might cause changes in space charge at boundaries of clouds, and there may be several ways in which this affects cloud microphysics, and then produce correlated changes in the weather and climate[5]. Generally, the storms and substorms can be caused by solar activities result in the HEEF enhancement, and then, the high energy electrons precipitate in the atmosphere will excite X-ray by bremsstrahlung; afterwards, the precipitated electrons and X-ray increase the ionization of the atmosphere, lead to the local conductivity increase. Finally, the increased conductivity makes the electric field to enhance. Therefore, the space-weather could affect the weather variation and global climate change under some conditions.

Above data presentation and the analysis have demonstrated that the HEEF could modulate

the atmospheric vertical electric field. In the meantime, a better understanding of how GEC influenced by high-energy particles also have been obtained. Qualitative attempts have been made to explain how the HEEF affects the vertical electric field of the atmosphere near ground. The future work is to do a quantitative study on the relation between them, and on how the weather and climate will respond if the precipitation-associated vertical atmospheric electric field changes.

3. Acknowledge

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4. References

1. Farrell, W.M. and M.D. Desch, *Solar proton events and the fair weather electric field at ground.* Geophysical Research Letters, 2002. **29**(9).
2. Holzworth, R. and F. Mozer, *Direct evidence of solar flare modification of stratospheric electric fields.* Journal of Geophysical Research, 1979. **84**(C1): p. 363-367.
3. Reagan, J.B., et al., *The Effects of Energetic Particle-Precipitation on the Atmospheric Electric-Circuit.* Journal of Geophysical Research-Oceans and Atmospheres, 1983. **88**(Nc6): p. 3869-3878.
4. Frank-Kamenetsky, A.V., et al., *Variations of the atmospheric electric field in the near-pole region related to the interplanetary magnetic field.* Journal of Geophysical Research-Space Physics, 2001. **106**(A1): p. 179-190.
5. Tinsley, B.A., *Influence of solar wind on the global electric circuit, and inferred effects on cloud microphysics, temperature, and dynamics in the troposphere.* Space Science Reviews, 2000. **94**(1-2): p. 231-258.
6. Tinsley, B.A., G.B. Burns, and L. Zhou, *The role of the global electric circuit in solar and internal forcing of clouds and climate.* Advances in Space Research, 2007. **40**(7): p. 1126-1139.
7. Tinsley, B.A. and L. Zhou, *Initial results of a global circuit model with variable stratospheric and tropospheric aerosols.* Journal of Geophysical Research: Atmospheres (1984–2012), 2006. **111**(D16).
8. Tinsley, B.A., L. Zhou, and W. Liu, *The role of volcanic aerosols and relativistic electrons in modulating winter storm vorticity.* Advances in Space Research, 2012. **50**(6): p. 819-827.
9. Roberts, W.O. and R.H. Olson, *Geomagnetic Storms and Wintertime 300-mb Trough Development in the North Pacific-North America Area.* Journal of Atmospheric Sciences, 1973. **30**: p. 135-140.
10. Tinsley, B.A. and G.W. Deen, *Apparent tropospheric response to MeV‐GeV particle flux variations: A connection via electrofreezing of supercooled water in high‐level clouds?*

Journal of Geophysical Research: Atmospheres (1984–2012), 1991. **96**(D12): p. 22283-22296.
11. Hays, P. and R. Roble, *A quasi‐static model of global atmospheric electricity, 1. The lower atmosphere.* Journal of Geophysical Research: Space Physics (1978–2012), 1979. **84**(A7): p. 3291-3305.
12. Roble, R. and P. Hays, *A Quasi‐static model of global atmospheric electricity 2. Electrical coupling between the upper and lower atmosphere.* Journal of Geophysical Research: Space Physics (1978–2012), 1979. **84**(A12): p. 7247-7256.
13. Kirkland, M.W., B.A. Tinsley, and J.T. Hoeksema, *Are stratospheric aerosols the missing link between tropospheric vorticity and earth transits of the heliospheric current sheet?* Journal of geophysical research, 1996. **101**(D23): p. 29689-29,699.
14. Mironova, I., B. Tinsley, and L. Zhou, *The links between atmospheric vorticity, radiation belt electrons, and the solar wind.* Advances in Space Research, 2012. **50**(6): p. 783-790.
15. Tinsley, B.A., J.T. Hoeksema, and D.N. Baker, *Stratospheric volcanic aerosols and changes in air-earth current density at solar wind magnetic sector boundaries as conditions for the Wilcox tropospheric vorticity effect.* Journal of geophysical research, 1994. **99**(D8): p. 16805-16,813.
16. Weimer, D., *A flexible, IMF dependent model of high‐latitude electric potentials having "space weather" applications.* Geophysical Research Letters, 1996. **23**(18): p. 2549-2552.
17. Weimer, D., *An improved model of ionospheric electric potentials including substorm perturbations and application to the Geospace Environment Modeling November 24, 1996, event.* Journal of Geophysical Research: Space Physics (1978–2012), 2001. **106**(A1): p. 407-416.
18. Frahm, R.A., et al., *The diffuse aurora: A significant source of ionization in the middle atmosphere.* Journal of Geophysical Research-Atmospheres, 1997. **102**(D23): p. 28203-28214.
19. Li, X.L., et al., *Long term measurements of radiation belts by SAMPEX and their variations.* Geophysical Research Letters, 2001. **28**(20): p. 3827-3830.
20. Li, X.L., et al., *Quantitative prediction of radiation belt electrons at geostationary orbit based on solar wind measurements.* Geophysical Research Letters, 2001. **28**(9): p. 1887-1890.
21. Tinsley, B.A., *A working hypothesis for connections between electrically-induced changes in cloud microphysics and storm vorticity, with possible effects on circulation.* Advances in Space Research, 2012. **50**(6): p. 791-805.
22. Larsen, M.F. and M.C. Kelley, *A study of an observed and forecasted meteorological index and its relation to the interplanetary magnetic field.* Geophysical Research Letters, 1977. **4**(8): p. 337-340.
23. Kniveton, D.R. and B.A. Tinsley, *Daily changes in global cloud cover and Earth transits of the heliospheric current sheet.* Journal of Geophysical Research-Atmospheres, 2004. **109**(D11).
24. Roldugin, V.C. and B.A. Tinsley, *Atmospheric transparency changes associated with solar wind-induced atmospheric electricity variations.* Journal of Atmospheric and Solar-Terrestrial Physics, 2004. **66**(13-14): p. 1143-1149.
25. Tu, W., et al., *Quantification of the precipitation loss of radiation belt electrons observed by SAMPEX.* Journal of Geophysical Research: Space Physics, 2010. **115**(A7): p. A07210.
26. Siingh, D., et al., *The atmospheric global electric circuit: An overview.* Atmospheric Research,

2007. **84**(2): p. 91-110.
27. Baumgaertner, A.J.G., et al., *Toward a comprehensive global electric circuit model: Atmospheric conductivity and its variability in CESM1(WACCM) model simulations.* Journal of Geophysical Research-Atmospheres, 2013. **118**(16): p. 9221-9232.
28. Funke, B., et al., *Composition changes after the "Halloween" solar proton event: the High Energy Particle Precipitation in the Atmosphere (HEPPA) model versus MIPAS data intercomparison study.* Atmospheric Chemistry and Physics, 2011. **11**(17): p. 9089-9139.
29. Jackman, C.H. and R.D. McPeters, *The effect of solar proton events on ozone and other constituents.* Solar Variability and Its Effects on Climate, 2004. **141**: p. 305-319.
30. Tinsley, B.A. and F.Q. Yu, *Atmospheric ionization and clouds as links between solar activity and climate.* Solar Variability and Its Effects on Climate, 2004. **141**: p. 321-339.

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